Annual Project Summary Report

The New England Seismic Network

USGS Award Number 04HQAG0020

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Project Summary

The operation of a regional seismic network to monitor earthquake activity in New England and vicinity is supported under this project. The purpose of this earthquake monitoring is to compile a complete database of earthquake activity in New England to as low a magnitude as possible in order to understand the causes of the earthquakes in the region, to assess the potential for future damaging earthquakes, and to better constrain the patterns of strong ground motions from earthquakes in the region. The New England Seismic Network (NESN) is operated by Weston Observatory of Boston College. This is a progress report for the time period from October 1, 2004 through September 30, 2005.

Regional Seismic Network Status

The New England Seismic Network (NESN) is operated by Weston Observatory of Boston College. During the time period of this report, the Weston Observatory NESN was comprised of 12 seismic stations (Figure 1). Eleven of the seismic stations are located within New England, and there is one station at Troy, NY.

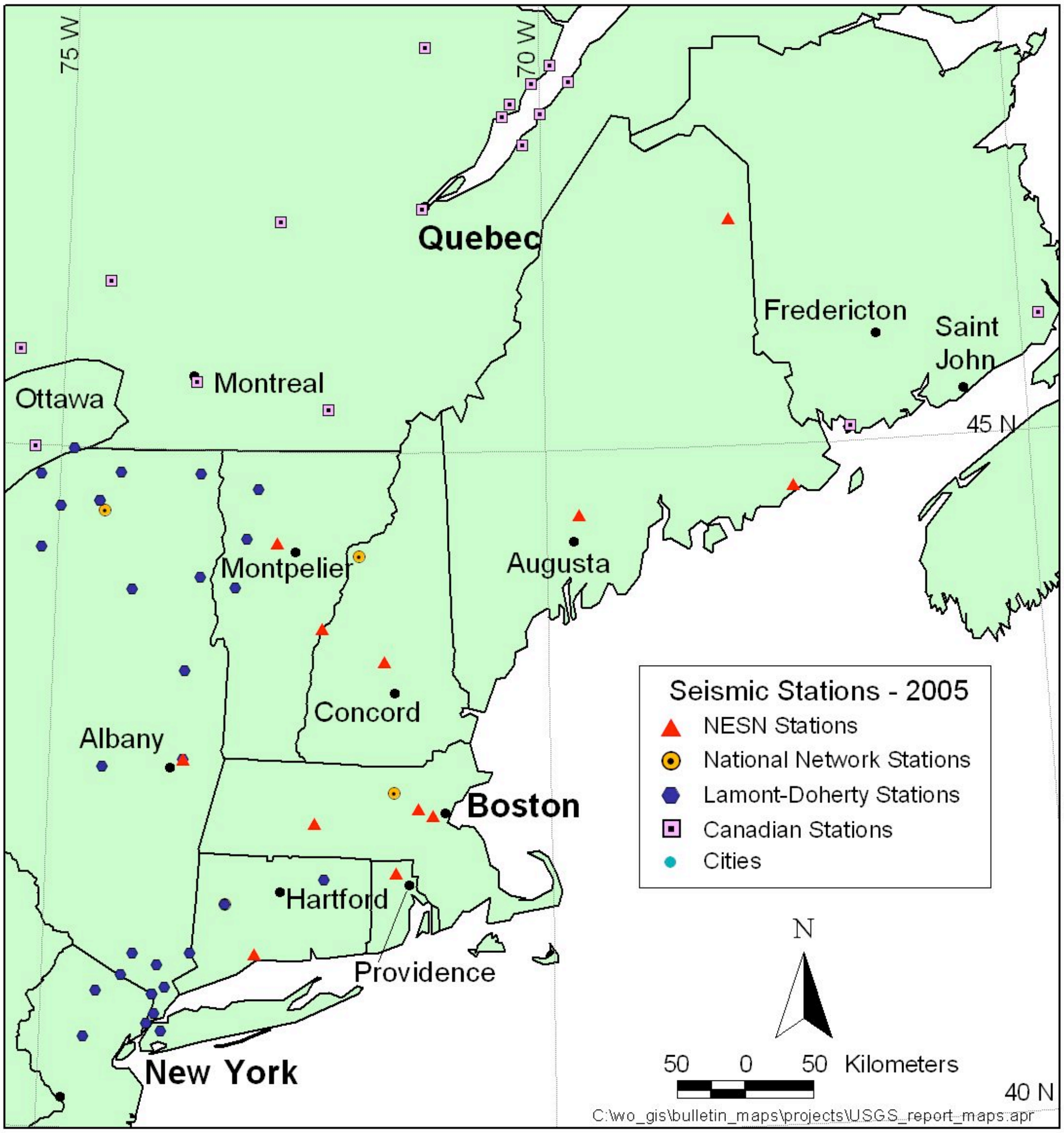

Figure 1. Stations of the Weston Observatory New England Seismic Network and other northeast networks from October 1, 2004 to September 30, 2005.

During the period of this report, efforts were made to standardize the NESN seismic instrumentation across New England and to bring it in line with ANSS standards. During this period, all NESN stations used the same seismometer, the Guralp CMG-40T with flat response to ground velocity between 30 sec and 30 Hz. However, two different types of digital dataloggers were used to record and transmit the seismometer analog outputs. At the beginning of this reporting period, five NESN stations (BRYW, FFD, HNH, QUA2 and WES) had been upgraded with Refraction Technology, Inc. RefTek 130-01, 24-bit digitzers, while the remaining seven NESN stations still utilized an older, Nanometrics, Inc. 16-bit gain-ranged digital recording system. The Nanometrics systems utilize PC's running the obsolete OS/2 operating system, and hence, they are becoming increasingly difficult and inefficient to support. By the end of this reporting period, an additional five (EMMW, PQI, TRY, WVL, and YLE) of the remaining seven Nanometrics stations had been upgraded with RefTek 130-01 units, making the NESN almost completely uniform in instrumentation. This is important as it greatly eases management and error debugging issues for an already stretched network staff, and also because it makes it much easier to provide metadata (e.g., instrument response information) to others who use the NESN data, since instrument response is now identical across almost all stations of the NESN.

The stations using the RefTek 130-01 digitizers provide continuous seismic data, digitized at 40 samples/second, via TCP/IP protocol and Earthworm to Weston Observatory, NEIC and other regional network processing centers. At the beginning of this reporting period, three of the older Nanometrics sites (EMMW, PQI, and WVL) also were sending their data via internet to the USGS NEIC in Golden, Colorado, which in turn sent those data via Earthworm to Weston Observatory. These three stations transmitted a continuous 1 Hz stream of filtered station data as well as 100 Hz windows containing unfiltered waveform data from time periods when the local station STA/LTA detector had identified a possible seismic signal. At all of the Nanometrics stations, the signals from the sensor were stored on the remote station PC in a continuous disk loop that was overwritten after about 3 weeks. Each Nanometrics system was configured such than a seismologist at Weston Observatory also could access the remote computer via an internet ftp connection (except at VT1 where only a dial-up telephone connection was possible) and transfer waveform data from the remote station to Weston Observatory. One station (BCX at Boston College) was not operational throughout this reporting period as it awaited new station equipment.

In the summer of 2004 the USGS had provided to Weston Observatory 5 RefTek 130-01 digitizers to upgrade and replace some of the NESN Nanometrics stations. Two of these RefTek digitizers were installed at station TRY in Troy, NY and at station YLE in New Haven, CT. However, a problem with the GPS timing systems was discovered in these new systems, and the same problem also appeared in the equipment that had been installed at the five stations that had been upgraded in 2003. These problems were fixed when they appeared with new GPS systems. A set of replacement GPS systems was received in September 2005, and plans were underway at the end of this reporting period to replace the older Nanometrics systems with RefTek 130-01 digitizers at stations EMMW, PQI and WVL in October 2005 (these replacement did in fact take place in October 2005). Once installed, these stations would transmit continuous three-component data at 40 samples/sec to Weston Observatory as well as to the USGS NEIC in Golden, CO. Thus, by the end of October 2005, the NESN would be comprised of ten RefTek stations and two (BCX and VT1) older Nanometrics stations. Weston Observatory is proposing to the USGS for equipment to replace its last two Nanometrics stations with RefTek units during 2006.

In addition to improving the uniformity of our network through the installation of new station equipment, Weston Observatory assumed primary responsibility for remote station control and data flow management from the USGS during this reporting period. At the beginning of this period, data from both the RefTek and Nanometrics digitizers was transmitted to NEIC servers running Earthworm and then was retransmitted via Earthworm from NEIC to Weston Observatory. Station remote management was handled by the NEIC via a RefTek RTPD server. As now configured, data flows directly from the remote digitizers to an RTPD server running on a Solaris machine at Weston Observatory and on to multiple Earthworm servers at Weston, which then forward the data to the NEIC and other interested users. This change in data flow is important as it reduces the number of hops each packet of data must make to reach the primary Earthworm server, and hence greatly reduces the transmission delay of realtime data.

Throughout the period of this report, Weston Observatory continued to modify and improve its wavelet-transform based automated event detector and identifier. An older version of this system was initially created and tested by Gendron et al. (2000) for the PC-based regional seismic network stations operated by Weston Observatory. An initial version of a new wavelet-based automated event detector and identifier, written in Matlab for use with Earthworm datastreams, began routine operation at Weston Observatory in August, 2003. This software system carries out a wavelet transform on the data from each station being received via Earthworm, and then it looks for detections of possible seismic events within each data stream based on the amplitude of the wavelet-transform coefficients. Once a possible event is detected, the time, wavelet-transform scale (each scale corresponds to a different frequency band) and energy of the event beginning are measured, along with the same parameters for the highest amplitude of the detected event. A measurement of the end time of the event (when it drops below the detection thresholds at all scales) is also made. Using these seven event measurements, a calculation is carried out, similar to that described by Gendron et al. (2000), to compute the Bayesian probability that the detection was a teleseism, regional earthquake, local earthquake, quarry blast, Rg wave from a quarry blast, or transient noise. The event type with the highest probability is considered the most likely identification for the detected event.

Modifications made to the code since it was first installed have greatly improved the accuracy and effectiveness of the automated wavelet-transform event detection and identification system. The code was modified to use the wavelet-transform event parameter measurements to estimate the origin time, epicentral distance and magnitudes (both coda-wave magnitude Mc and Lg-wave magnitude MLg) for each detection. Several event associators have been implemented that make use of the event identification system to associate detections from different stations that have a common event type.

One event associator is designed to associate teleseismic P wave arrivals. For event detections from two or more different stations that have a high probability of being a teleseismic signal, the associator checks to see if the arrival times at these stations are close enough in time to be the initial P wave of a teleseism. If this is true for 3 or more stations, the associator then tries to locate the teleseismic by fitting a plane wave to the detected P arrival times, and from this plane-wave fit estimate the back azimuth and epicentral distance of the teleseismic source.

A second associator works on signals that have a high probability of being a regional or local earthquake. In this case, the primary parameter that is used to associate the signals from two different stations is the estimated origin time of the event signal at each station. If the estimated origin times at two stations are within some preset limit, a possible local or regional event association is declared. If three or more stations are found to have associated origin times, an automatic event location and set of Mc and MLg magnitudes are computed under the assumption that a local or regional event has been detected. The automated event locator is programmed to send an email to selected internet addresses and to page the duty seismologist at Weston Observatory immediately after the event location and magnitude have been generated if the observed arrival times are close to those predicted using the automatic event location. In the summer of 2005, this system was modified to allow a station to associate just its peak arrival time with a local or regional event that has been detected on at least one other stations. This modification was made to cover those cases where, for a station at a larger distance from an epicenter, the wavelet-transform detector did not detect the initial P wave of the event but did successfully detect the Lg wavetrain. This system has proven to be quite good at automated event detection and location with the sparse regional network operated in New England and vicinity. In fact, as is discussed below, this system has started detecting small earthquakes that had been previously missed by earlier event detection schemes.

A third associator has also been implemented in the automated wavelet-transform event detection and identification system. This associator looks to accumulate the event detections at different stations from a common quarry blast source. Because it is important to be able to discriminate between quarry blasts and earthquakes for accurate earthquake monitoring, those detections with a high probability of being a quarry blast (either where both the P wave and surface waves were detected or where just the Rg-wave was detected) are associated. In most cases these associations have proven to be quite accurate, and they help the analyst greatly in discriminating between earthquakes and quarry blasts. On a typical summer day, as many as 12-15 quarry blasts can be routinely observed, so each day there are many events that the seismic analyst must verify are not local or regional earthquake activity. If quarry blast arrivals at three or more stations associate, the program attempts to locate the quarry blast.

The wavelet-transform event detection, identification and association/location system has become an indispensible tool for greatly improving the efficiency of earthquake monitoring using the spatially sparse regional seismic network that Weston Observatory operates in the New England region. The improvements made during the past two years have greatly augmented the capabilities for discriminating among the different possible event detections (teleseisms, regional/local earthquakes, quarry blasts, or noise), have increased the sensitivity of detecting and locating small earthquakes, and have led to the implementation of a reliable automated system for earthquake location and magnitude determinations, from which automated pages and emails are now sent out concerning these earthquake determinations. The system was detected an average of 12 quarry blasts and about 1 teleseism during weekdays in the fall of 2005. One or two local earthquakes per month are being detected in New England, along with a comparable number of earthquakes from nearby areas in Canada and the middle Atlantic states. Plans at Weston Observatory to increase the number of seismic stations in northern New England should further enhance the capabilities of this system to detect local and regional earthquakes.

Another effort to improve the reliability and robustness of the event identification system has been the testing of a second event identifier as part of the wavelet-transform system. This second system compares the entire wavelet-transform "spectrum" of the event at all scales in with a collection of standard wavelet-transformed "spectra" found from known teleseisms, local/regional earthquakes, quarry blasts, and noise transients (Zhu and Ebel, 2004; Ebel, 2004). In one test, this method has been applied at the beginning of an event detection to attempt a rapid identification of the type of seismic event that is being detected. It is hoped that this system can aid in event identification, and can also be adapted for use as an immediate event identifier as part of a seismic early warning system. The Zhu and Ebel (2004) event identification system still must undergo further refinement before it can be used reliably.

There remain some data processing shortcomings with the Earthworm data being received at Weston Observatory that must still be addressed. Earthworm's Waveviewer module, which is currently being used at Weston Observatory by a seismic analyst as one way to observe the waveforms of a seismic event, does not provide a direct means to measure the amplitudes of the seismic signals it displays. Furthermore, Waveviewer does not have the capability of filtering seismic traces. Thus, it is not possible with the Waveviewer system to remove either low-frequency or high-frequency background noise from earthquake signals. These problems are being addressed at the present time by extracting the Earthworm waveform data into SAC files and then reading them into another program where filtering can be carried out and where arrival times and amplitudes can be read. A third program (HYPO78) is used to compute the event locations and magnitudes. The current data analysis methods at Weston Observatory that employ multiple software packages that do not communicate directly with each other is inefficient, but it is necessary in order to perform a proper analysis of the seismic data at present.

Weston Observatory continues to search for new sites for regional seismic network stations in New England. Weston Observatory personnel have continued to work with the Maine Geological Survey and the USGS to locate a USNSN national backbone station in central Maine. An acceptable site has been identified, and USGS personnel carried out preliminary noise investigations of the site toward the end of this reporting period. Weston Observatory is also working with universities in Keene, NH, Farmington, ME, Gorham, ME and Orono, ME to develop new seismic stations at or near those universities. Finally, Weston Observatory has been working with officials at a dam near Springfield, MA to bring the data from a digital strong-motion station on-line via the internet. It is ultimately the goal of Weston Observatory to bring the strong-motion data from this station into Weston Observatory via Earthworm and to incorporate the data into the routine event processing scheme. Once implemented, this would be the first real-time stream of strong-motion data directly to Weston Obervatory from a site in New England.

Weston Observatory continues to cooperate with other regional network operators in northeastern North America and beyond (Lamont-Doherty Earth Observatory, the USGS NEIC, and the Canadian Geological Survey) in earthquake detection and analysis for events in the region. Event arrival time readings, waveforms, and hypocentral information are routinely exchanged between the Weston Observatory and these other groups. Weston Observatory continues to produce a quarterly seismic network bulletin for the New England area. That bulletin is produced in html format and is posted on the Weston Observatory web pages as soon as possible after the quarter ends. Lists of recent earthquakes are also maintained on the Weston Observatory web site, along with links to other important sites with earthquake information for the region. Weston Observatory posts weekly earthquake probability forecasts on its web site, and it is working with Lamont-Doherty Earth Observatory to implement ShakeMap capabilities in the northeastern U.S.

Accomplishments During the Report Period

Seismic Monitoring

The Weston Observatory NESN seismic stations detected a number of earthquakes from New England and vicinity from October 1, 2004 to September 30, 2005. A total of 33 local and regional earthquakes from New England and vicinity with Lg magnitudes from 0.2 to 5.3 were detected and located by the network (Figure 2), some of which were locally felt by residents in New England. In addition to these events, some microearthquakes and suspected events, too small to be located, were detected by the network. The number of earthquakes during this reporting period is significantly greater than that from recent years. This in part is due to the improvements in event detection and identification that were discussed in the previous section of this report, and in part is due to an increase in the seismic activity in Canada.

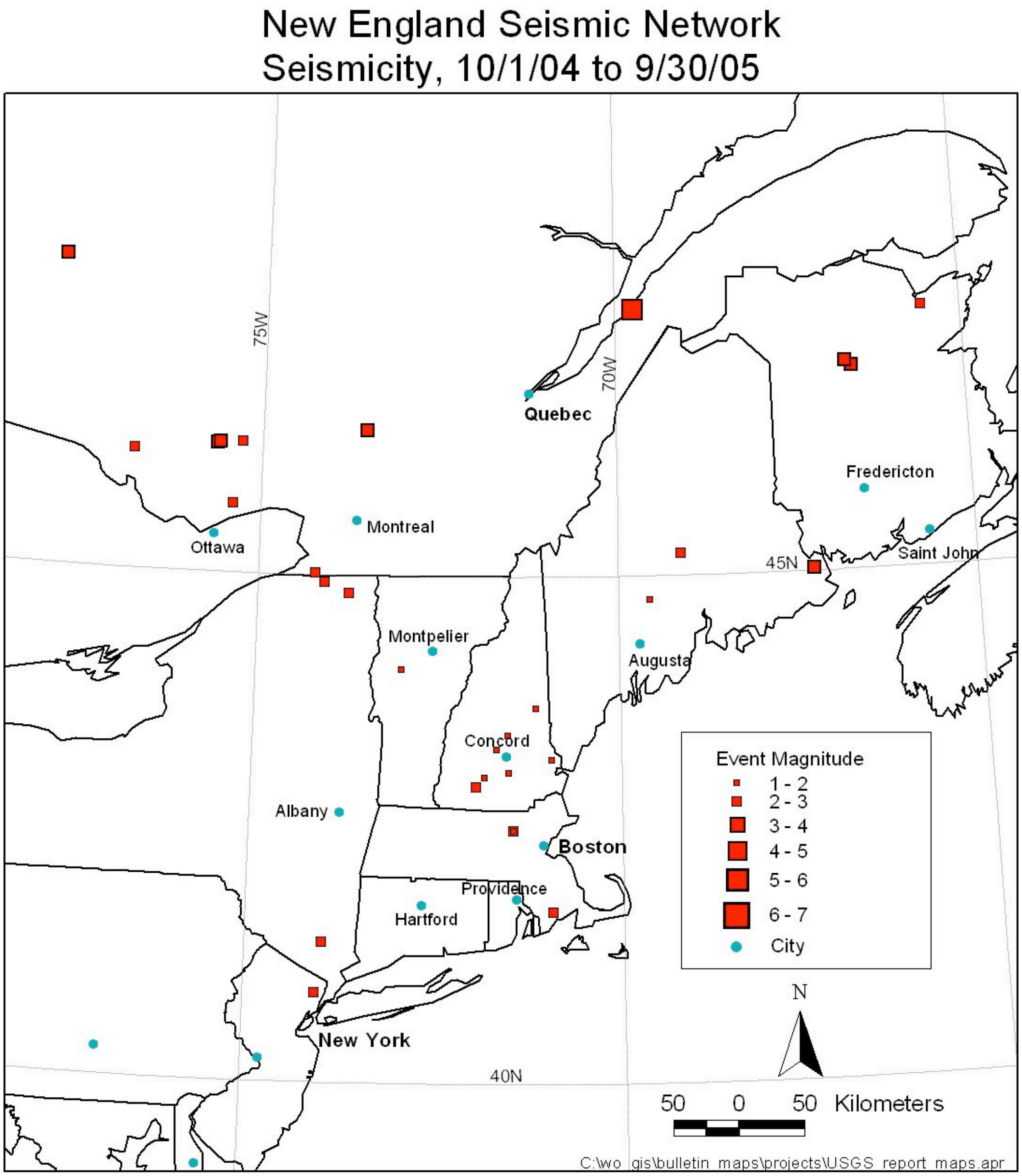

Figure 2. Seismicity of the northeastern U.S. and southeastern Canada detected by the Weston Observatory New England Seismic Network from October 1, 2004 to September 30, 2005.

There were several notable earthquakes during this reporting period. The most significant event was an MLg 5.3 earthquake (moment magnitude **M** about 4.7) on March 6, 2005 that was centered near Riviere-du-Loupe, Quebec, just north of the northern tip of Maine. This earthquake was felt noticeably throughout the northern half of New England, with scattered reports from further south in the region. This was the largest earthquake that was felt in New England since the ML 5.1 (**M** 5.0) earthquake at Au Sable Forks, NY in April, 2002. The Riviere-du-Loupe event was centered at the edge of the very active Charlevoix seismic zone along the St. Lawrence River in Canada, and it served as a reminder of the hazard of that active seismic zone. The closest NESN station to this earthquake was PQI, at an epicentral distance of 169 km.

Of earthquakes centered in New England, the strongest was an MLg 3.5 earthquake that was centered in eastern Maine southeast of the town of Calais. This area was the site of an MbLg 5.9 earthquake in 1904 and some other earthquakes above MbLg 5 in the nineteenth century (Burke and Leblanc, 1985). Instrumental monitoring since 1975 has detected a diffuse pattern of earthquake activity in the vicinity of Passamaquoddy Bay at the Maine-New Brunswick border (Figure 3). The local tectonic significance of the earthquake activity in this area is unclear, but it does indicate that this remains an active area with the potential to produce earthquakes with magnitudes greater than 5.0. Unfortunately, due to the sparseness of the regional seismic networks in Maine and New Brunswick, it was not possible to determine a constrained focal mechanism for the 2005 event.

A small earthquake of MLg 2.0 followed by two aftershocks (MLg 1.2 and 0.2) took place on October 8, 2004 near Littleton, Massachusetts, a suburb about 30 km northwest downtown Boston. Over the past 15 years, a small earthquake has been detected within 10 km of the Littleton area on average about once every other year. Why the Littleton area experiences such steady small earthquake activity is not well understood since the seismicity does not neatly correlate to any single geologic structure. However, the regularity of the seismicity may be indicative that these small events are very late aftershocks of a large earthquake that took place before historic time, as postulated by Ebel et al. (2000). If this is true, then it suggests that a stronger and perhaps even damaging earthquake might be possible in the northwestern surburbs of the Boston metropolitan area.

A couple other earthquakes worthy of special mention took place in New England during this reporting period. One was an MLg 2.3 earthquake that was centered near New Bedford, Massachusetts on April 4, 2005. This earthquake took place along the south Atlantic coast of Massachusetts, a broad area that has experienced felt earthquakes every few years during the past couple of decades. It generated a number of felt reports and media interest. Another minor earthquake of note was an MLg 1.5 earthquake that took place in the Ossipee, New Hampshire area on April 10, 2005. A pair of magnitude 5.5 earthquakes occurred in this area in December 1940. If the 2005 event is a late aftershock of the 1940 shocks, then its location can help refine the location the 1940 earthquakes since the epicenters of those larger events are poorly known due to the sparse station spacing at that time.

As discussed earlier, the wavelet-transform event detection and identification system that is now being operated at Weston Observatory has improved the sensitivity of the earthquake monitoring effort in New England. A comparison of the numbers and magnitudes of the earthquakes detected in New England during this reporting period compared with those numbers from previous reporting periods demonstrates this improvement. As shown in Table 1, the number of earthquakes with magnitudes below 2.0 detected in New England was significantly greater during the past 12 months in comparison with the number detected during the previous three 12-month periods. What is most telling is the large number of detected earthquakes during this reporting period that were not reported felt by local residents. Prior to 2003, the only earthquakes in New England and immediately surrounding areas that were detected and located by Weston Observatory were those from which felt reports had been received and an earthquake was confirmed by visual inspection of the data from the regional seismic network stations. This situation changed with the installation of the Earthworm system for continuous data communication and with the development and implementation of the automated wavelet transform system for event detection and identification. All of this improvement in small earthquake detection has taken place for earthquakes in southern and central New England where most of the Weston Observatory regional seismic stations are located. A similar improvement in detection capabilities in Northern New England must await the installation of the new RefTek equipment at the existing stations and the installation of new stations in Maine (which experiences about half of the earthquakes in New England each year) to improve the regional network density in that state. The goal of the improved monitoring of small earthquakes in the region is to provide more data for understanding the relationship of the earthquake activity and the geologic structures in the region, with the aim of identifying which structures are seismically active and what magnitude earthquakes may be possible on those structures.

During this reporting period, Weston Observatory continued its web site offering weekly estimates of the probability of a felt earthquake in New England. The temporal probability is based on the work of Ebel and Kafka (2002), while the spatial probability is based on research published by Kafka and Levin (2000) and Kafka (2002). A link called "Earthquake Probability" on the Weston Observatory web page (www.bc.edu/westonobservatory) shows the probability of a felt earthquake in New England for each upcoming 7-day period. Also shown on this web page is a map of those areas in New England that have about a 67% probability of being the epicenter of an earthquake of MLg >= 2.7 during the 7-day period. During this reporting period, the only earthquake large enough to trigger a forecast of increased earthquake probability was the MLg 3.5 eastern Maine earthquake of September 25, 2005. It was not followed by any earthquake above MLg 2.7 during the next 7 days.

Table 1.

Number of Detected Earthquakes in New England from October 1, 2001 to September 30, 2005

Year	Total # Earthquakes	# M >= 2.0 Earthquakes	# M < 2.0 Earthquakes	# Earthquakes Not Felt
10/1/04-9/30/05	15	5	10	8
10/1/03-9/30/04	7	5	2	2
10/1/02-9/30/03	9	7	2	0
10/1/01-9/30/02	17	12	5	0

Figure 3. Seismicity of the Passamaquoddy Bay area between Maine and New Brunswick, Canada detected by the Weston Observatory New England Seismic Network from January 1, 1975 to September 30, 2005. The largest earthquake shown here was the MLg 3.9 event on September 16, 1994.

Data Dissemination

Weston Observatory continues to archive the waveform data for the seismic stations that it operates. Weston Observatory has the capability to convert the waveforms, routinely stored in Nanometrics format PC stations, to either ASCII or SAC for external distribution. The new

NESN manager, Dr. Michael Hagerty, was the developer of the waveform viewing software WebSeis that is currently used by LDEO for display of their seismic station waveforms on the LDEO web pages. This software makes digital seismograms of each station/channel in various frequency bands (SP,LP,BB) and allows zooming, filtering and plotting of select windows of station waveform data via a web interface. This software will be installed at Weston Observatory, providing web access for viewing and distribution of NESN waveform data and metadata. Weston Observatory also is working to develop capabilities to deliver SEED waveforms of local events to the IRIS DMC, but that work was not completed by the end of this report period. In addition, Weston Observatory contributes hypocentral data to the ANSS composite catalog and to the USGS NEIC on a routine basis as soon as possible after local earthquakes take place.

Weston Observatory maintains a web site with information about local earthquakes:

- http://www.bc.edu/westonobservatory

Currently available on the web page is the full catalog of northeastern earthquake activity to 2005 along with recent quarterly reports of the seismicity detected by the NESN. Weston Observatory attempts to regularly maintain and update its web pages with the latest information on earthquakes in the region.

Financial Report and Personnel Status

During the time period of this report, the funding for this project was spent in accordance with the arrangements agreed upon in the cooperative agreement between Boston College and the USGS. There was one important change in personnel for this project during the reporting period. Edward (Ned) Johnson, who had been project engineer since 1982, retired during the summer of 2004. His replacement, Dr. Michael Hagerty, began work in January 2005.

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